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The development of apartment house life cycle CO_2 simple assessment system using standard apartment houses of South Korea

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ABSTRACT

This study classified the life cycle of buildings into a construction stage, an operation stage, a maintenance stage and a dissolution/disposal stage, and proposed a CO_2 assessment method for each stage for the purpose of creating a simple life cycle CO_2 assessment system for apartment houses.

Specifically in the construction stage, major construction materials that are the source of more than 80% of CO_2 emissions produced during building construction were selected, and a method of evaluating CO_2 emissions for five standard apartment houses was proposed. In addition, amounts of CO_2 emissions generated during the building operation stage and the maintenance stage were calculated based on the "Green Home Certification System" and the "Apartment House Building Long Term Repair Plan and Repair Rate" of the Korean Ministry of Land, Transportation and Maritime Affairs. For the dissolution/disposal stage, a CO_2 assessment method was proposed that would enter into a database the amount of oil used by disposal equipment and other related types of machines, and analyze the process of waste treatment. Also, the potential of applying a simple assessment program was evaluated in connection with a life cycle CO_2 assessment simulation utilizing an actual apartment building.

Consequently, the results of a building life cycle CO_2 assessment using standard apartment houses as proposed in this study indicated a figure of 14,013.66 ton-CO_2. That figure is similar to 11,640.00 ton-CO_2 for existing apartment houses. In particular, the results of material production in the construction stage and CO_2 calculation in the maintenance stage indicated significant results closely approximating the 80% of CO_2 emissions attributed to construction material production noted earlier in this study at first.

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1. Introduction

1.1. Background and objective of this study

The development of international environmental agreements in response to global warming has stretched from the 1970s to 2009s. Beginning with the Declaration of the United Nations Conference on the Human Environment issued in Stockholm in June 1972, which called on the peoples of the world to make efforts to preserve the Earth in the face of a worldwide environmental crisis, the concept that "present development shall meet the requirements of the present generation and future generations fairly" was proclaimed as the official goal of the UN. A further goal of such international environmental agreements is to require the reduction of CO_2 emissions in all industries [1–3].

In particular, the construction industry, a sector of the economy that accounts for more than 40% of natural resource consumption, more than 30% of energy consumption and more than 30% of CO_2 emissions, is becoming the focus of a major international argument over how to preserve the global environment. Since the early 1990s in environmentally conscious developed countries, studies at the national government level have been undertaken on the assessment of building life cycle CO_2 [4–10].

In Korea, a variety of environmentally friendly architectural techniques have been developed as a way to make developments sustainable and strengthen the nation's international environmental competitive power. But it is true that studies that assess the amount of building CO_2 emissions have not kept pace with the development of environmentally friendly architectural techniques. In addition, while building CO_2 assessments should be routinely performed in the course of construction planning and basic design stages, and while the results of those assessments should be routinely incorporated in the design stage, the fact is that in practice such programs are insufficiently developed at present [11,12].

Therefore, the purpose of this study is to develop an apartment house life cycle CO_2 simple assessment system that can measure the CO_2 emissions of a building even without construction material quantity calculation data or the results of energy consumption simulation analysis in construction planning and the basic design stages.

1.2. Method and procedure of the study

In this study, the method of assessing CO_2 in each stage was proposed by classifying the building life cycle into a construction stage, an operation stage, a maintenance stage and a dissolution/disposal stage. In other words, in the construction stage, CO_2 emissions generated from major construction materials that make up more than 80% of CO_2 emissions associated with apartment house construction were selected. Then a database was established for the major CO_2-emitting materials for the five standard models proposed in "The Construction Standard and Performance of Environment Friendly House Construction" (hereinafter called the "Green Home Certifying System") announced by the Korean Ministry of Land, Transportation and Maritime Affairs. In addition, the amounts of CO_2 emissions generated in the building operation stage and the maintenance stage were calculated based on the "Green Home Certification System" and the "Apartment House Building Long Term Repair Plan and Repair Rate" developed by the Korean Ministry of Land, Transportation and Maritime Affairs. In the dissolution/disposal stage, a CO_2 assessment method was proposed that would incorporate into a database the amounts of oil used by disposal equipment and related machines, and which would then analyze the process of waste treatment. Also, the potential of applying a simple assessment program was evaluated through a simulation of the life cycle CO_2 assessment of actual building using the proposed apartment house life cycle CO_2 simple assessment program.

2. Discussion on building life cycle CO_2 assessment study

2.1. Definition of building life cycle CO_2 assessment

The term building life cycle CO_2 assessment refers to the quantitative assessment of the amount of energy consumption and the amount of CO_2 emissions generated during a building life cycle period, which is classified into a construction stage, an operation stage, a maintenance stage and a dissolution/disposal stage. For such a quantitative assessment of building life cycle CO_2, the life cycle of a building should be classified by each stage and the CO_2 assessment method should be deduced after setting up a CO_2 assessment range for each stage [13,14].

2.2. Analysis of Building Life Cycle CO_2 Assessment Program

Table 1 shows a representative program for building life cycle CO_2 assessment. First off, a Life Cycle Assessment Program for buildings (SUSB-LCA) developed by Sustainable Building Research Center of Hanyang University, Korea, classifies building life cycle CO_2 into a construction stage, a use/maintenance stage, and a dissolution/disposal stage, and calculates the amount of energy consumption and CO_2 emissions of each of those stages. In

Table 1
Domestic and Overseas Building Life Cycle CO_2 Assessment Program.

Program	Developed country	Organization	Developed year	Intended building	Feature
SUSB-LCA	Korea	Sustainable Building Research Center of Hanyang Univ.	2007	All the buildings	Assesses building life cycle CO_2 and cost Assesses energy consumption amount and CO_2 emission amount by the stages. Compares assessed building and countermeasure building Program upgrade is easy.
AIJ-LCA	Japan	Japan architectural society	2003	All the buildings	Assesses building life cycle CO_2 and cost Wide assessment in industry specific analysis method Composed in Excel worksheet type. Calculates CO_2, NOx, SOx emission amounts and energy using amount.
GEM-21P	Japan	Shimizu construction	2008	All the buildings	Utilizes the carbon dioxide unit data of Japan architecture society Calculates CO_2 emission amount with the use of building usage and scale data Assess life cycle ranging from material, construction, operation, maintenance and dissolution Assess CO_2 emission on remodeling.
Carbon navigator	Japan	Daisei construction	2009	House, office	Composed of 5 software like PAL-navi, ERR-navi, aurora, CarbonCalc and PAL-auto calculation Assesses by the stages PAL-auto calculation pursues efficiency in connection BIM Conducts simulation of CO_2 reduction measures in the early stage of planning.
BECOST	Finland	VTT	2003	All the buildings	Web based assessment offers users easy access Offers assessment and analysis results by various stages Processes various data like structure type and material, land area and endurance period, etc.
LISA	Australia	University of Newcastle	2003	All the buildings	Composed of simple design interface Offer high performance of material production analysis with the use of LCI DB Processes data in simple checklist form.
ENVEST2	UK	BRE	2003	Office	Offers users high accessibility through web based assessment Assesses with eco-point the unique indicator of program Offers various analysis results.
LCA-MCDM	U.S.	IEA (International Energy Agency)	1999	Office	Reflects weighted value on standard proposal through general designing assessment program Compares standard building.
Eco-Quantum	Holland	W/E Sustainable Building	1996	House, office	The first computer program based on building LCA Utilized in LCA assessment of construction industry Rain processing facility is considered.

addition, with the capability to compare levels of energy consumption and CO_2 emissions by each stage of a building where environmentally friendly construction techniques are applied with those of existing buildings, the program offers data renewal and upgrades such as additions of construction materials and unit modifications. Major functions include calculations of CO_2 through the life cycle of a building, comparisons of CO_2 values calculated by the application of each environmentally friendly construction technique, and calculations of the amount of CO_2 generated through the life cycle of a building as determined by the amounts of material used in its construction, and the amount of energy consumed during its operation stage and the amount of waste produced in the dissolution stage [15].

AIJ-LCA developed by the Japan architectural society can assess the amounts of emissions of greenhouse gases – CO_2, NOx, Sox – and measure energy consumption generated throughout a building's life cycle. This program assesses the abovementioned greenhouse gas emissions and level of energy consumption during the construction stage by measuring construction materials and energy consumed during the building's operation stage through the use of simulation results. The amount of emissions and the level of energy consumption of the standard building and the

assessed building can then be compared during each stage as well as throughout the life cycle.

GEM-21P, a life cycle CO_2 assessment program developed by Shimizu Construction of Japan, utilizes the CO_2 unit data of the Japanese architectural society in an assessment like the abovementioned AIJ-LCA. In addition, the best feature of this program is that it can calculate the level of CO_2 emissions by entering building usage and scale data. It can also be used to make assessments during remodeling. Carbon navigator, a program developed by Daisei construction of Japan, is composed of five types of software: PAL-navi, ERR-navi, aurora, CarbonCalc and PAL-auto calculation. And since the software can interlink with BIM, the one at issue recently, and perform assessments at each stage, it promotes efficient assessments by utilizing CO_2 reduction countermeasure simulation at an early stage of planning.

On the other hand, BECOST, a web-based building CO_2 assessment program developed by VTT Research Center of Finland, offers users good accessibility and can be used to make assessments in various stages, from planning to the completion of construction of a building. LISA of Australia, a CO_2 assessment program of life cycle perspective jointly developed by Newcastle University and the BHP Research Center, is intended for all types of buildings and simple civil engineering facilities. Composed of a simplified input/output interface, and intended to assess the amount of CO_2 generated with the use of LCI DB of construction material, this program offers outstanding performance in the analysis of material production [16]. ENVEST2, a building life cycle environmental performance assessment program developed by BRE of the United Kingdom, is mainly intended for analyses of office buildings, and performs web-based assessments. This software offers users outstanding accessibility. The assessment and results of this program are expressed as Eco Point, the unique indicator of ENVEST. In general, 1 Eco Point is equivalent to the same amount of CO_2 as the amount of water resource of 1.38 m^3 [17].

LCA-MCDM, a general design assessment program developed in 1999 by the International Energy Agency, is largely composed of six assessment items: a life cycle cost element, a resource load element, an environmental load element, an architectural aesthetic element, an indoor quality element and a functional element, and it can make comparisons with standard buildings. It is mainly intended to assess office buildings. Eco-Quantum is the first building LCA-based computer program developed by W/E Sustainable Building of the Netherlands, and has as its main feature the capability to assess various conditions such as the effects by energy consumption through the life cycle of buildings and maintenance and construction-related parts durability.

In addition, there are other varieties of software like national Life Cycle Inventory (LCI), a database-based program developed by the Korean Ministry of Environment, PASS LCA of the Korea Certification Association, and the APESS program of the Korea Institute of Construction Technology. These programs require construction material data to perform their analyses and have difficulty making assessments of a building's life cycle.

In addition, in overseas cases, programs like Simapro, EQUER, OGIP, Eco-soft, ESCALE and LEGEP are out in the market. And in Korea K-LCA, developed by the Korea Institute of Construction Technology, and ECO-Pia, developed by Samsung Construction of Korea, are available [18–20].

Compared with the abovementioned programs, SUSB-LCA enables easy assessment of building life cycle CO_2 and offers outstanding performance of data renewal. BECOST and ENVEST2 offer users easy access and various analytical results but require many hours to calculate CO_2 due to the large number of input items required to make the calculation. In addition, AIJ-LCA and GEM-21P also can perform various comprehensive assessments of the stages of the life cycle, but because they too require many direct input items, they require many hours to perform their assessments.

On the other hand, LISA of Australia possesses an outstanding capability to analyze construction material production by utilizing the LCI database of many materials and requires relatively fewer assessment hours to perform its assessments owing to its simple input method. But its capability of providing a detailed analysis of CO_2 is limited [21].

3. Proposal of apartment house life cycle CO_2 simple assessment system

3.1. Overview

This study proposes a simple CO_2 assessment system that can assess the life cycle CO_2 of apartment buildings even without data pertaining to quantity of construction material and the results of energy simulation analysis of the operation stage.

To that end, the building life cycle was classified into a construction stage, an operation stage, a maintenance stage, and a

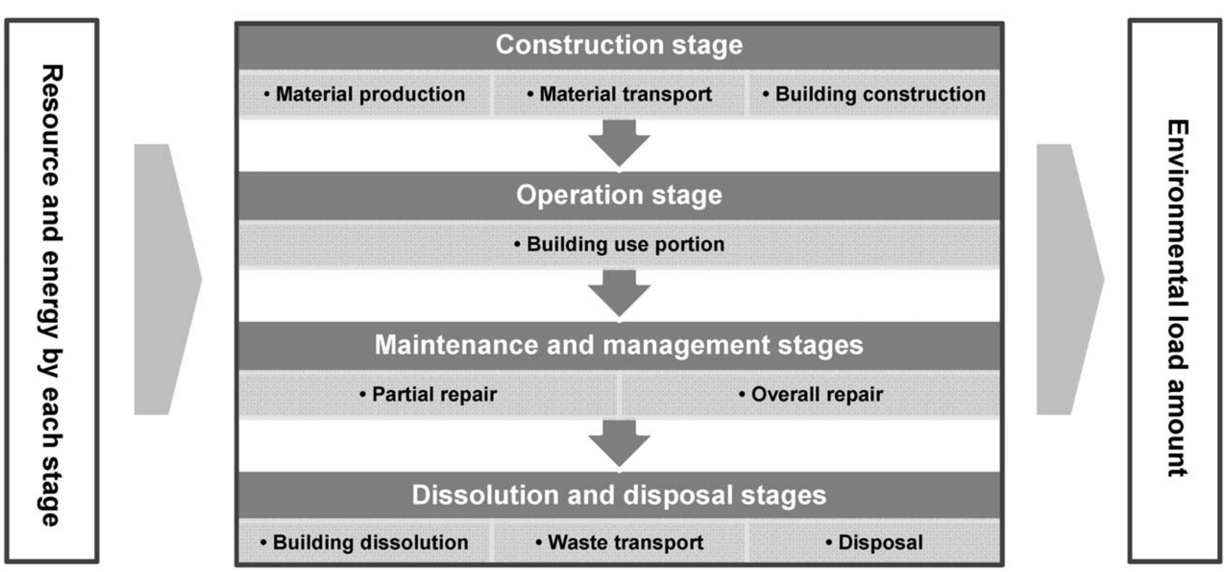

Fig. 1. Apartment house life cycle CO_2 assessment process.

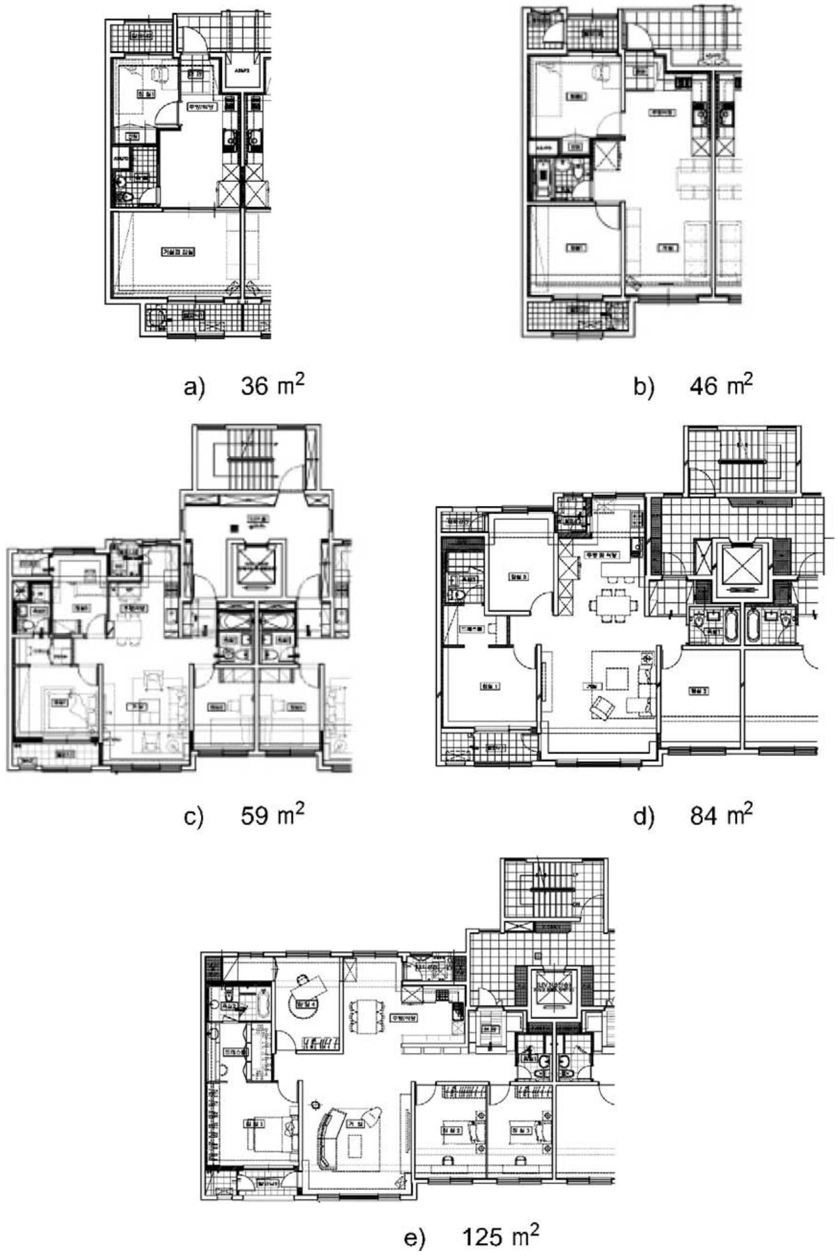

Fig. 2. Plane drawing of the unit household of Korea Green Home Certification System.

dissolution/disposal stage, and a method of CO_2 assessment for each stage was proposed. Fig. 1 shows the apartment building life cycle CO_2 assessment process proposed in this study [22–24].

3.2. Construction stage

3.2.1. Overview

In this study, the proposed method of CO_2 assessment in each stage classified the construction stage into a material production stage, a material transport stage and a building construction stage.

In particular, in the material production stage, major CO_2-emitting construction materials that make up more than 80% of CO_2 emissions were selected among the building materials used in construction. These account for about 85% of CO_2 emissions generated during the production of building materials. From them we can develop a method of CO_2 assessment by construction material production even without data on the quantity of these construction materials. In addition, a total of 90 types of apartment house standard models (hereinafter referred to as "standard apartment house") were proposed by combining dedicated area, number of households and number of stories by the area type based on five planes proposed in the Green Home Certification System of Korea as shown in Fig. 2 [25]. A CO_2 assessment in the material production stage was made possible only with the inputs of dedicated area, number of households and number of stories by area types in the construction planning and the basic design stage by establishing the quantity calculation database of major CO_2-emitting construction materials on the proposed standard apartment houses.

3.2.2. Material production stage

(1) Selection of CO_2-emitting major construction materials

In this study, major CO_2-emitting construction materials that make up more than 80% of CO_2 emissions among the materials used in construction were selected as previously

Table 2
Major CO_2 emitting construction materials of building construction.

Major materials group	CO_2 generation ratio
Reinforced steel	42.37%
Ready mixed concrete	23.72%
Plywood	4.03%
Concrete product	3.47%
Industrial plastic product	3.37%
Paint and varnish	3.13%
Total	80.09%

mentioned. To that end, the construction contents of an apartment building that was completed in May 2004 were analyzed. As a result, the amount of CO_2 emissions generated by the construction material production process as determined by the types of buildings constructed were analyzed and found to make up about 85% in the construction stage, specifically 352.36 kg-CO_2/m^2 in building construction, 11.15 kg-CO_2/m^2 in civil construction, and 49.68 kg-CO_2/m^2 in equipment construction. The major CO_2-emitting construction materials that make up 80% of CO_2 emissions among the materials used in construction were selected as shown in Table 2. The CO_2-emitting major construction materials include six kinds: steel reinforcement, ready-mixed concrete, plywood, concrete product, industrial plastic product, paint and varnish. The CO_2 emission ratios of each construction material are as follows [26].

(2) Establishment of database for CO_2-emitting major construction materials

The quantities of major materials were calculated on the total of 90 types of standard apartment houses based on the five planes proposed in the Green Home Certification System of Korea as previously mentioned in "Section 3.2." Table 3 shows the composition of the standard apartment house proposed in this study. According to Table 3, standard apartment houses are composed of three types of dedicated areas, three types of number of households, and six types of numbers of stories.

Therefore, in this study, six types of major CO_2-emitting construction materials that account for more than 80% of CO_2 emissions were calculated for a total of 90 types of standard apartment houses. A total of 71 detailed items relating to these materials were included in the calculations by applying unit work costs based on the construction sector (hereinafter referred to as the "construction standard resource cost"). A Korea construction standard resource cost was calculated for each major material. Fig. 2 shows the plane drawing of a unit of a standard apartment house of the Korea Green Home Certification System selected for this study. In addition, Table 4 shows the contents of the major CO_2-emitting construction materials found in a standard apartment house, and as an example, Table 5 shows the contents of unit work cost calculation on plywood.

(3) Establishment of database for CO_2-emitting major construction material unit

In general, methods of analyzing units of construction materials are broadly classified into an individual integration method, an industrial association analyzing method, and a mixed analysis method [27,28]. In this study, the CO_2 calculation was made possible through production of CO_2-emitting major construction materials only through construction planning and entering of dedicated area, number of households and number of stories in basic design stage by establishing CO_2 unit database for CO_2-emitting major construction materials as shown in Table 6 after mixing 94

Table 3
Composition of standard apartment house.

Constitution	Description
Lettable area	36 m^2, 46 m^2, 59 m^2, 84 m^2, 125 m^2
Block arrangement	Flat type: the floor plan is a straight line Tower type: the ratio of the short side to the long side of the plan is 1:2 or less
Combination of living units	Flat type: one combination (two-unit combined flat type) Tower type: two combinations (four-unit combined flat type, four-unit combined tower type)
Height of ceiling	2.9 m: air supply and ventilation systems are taken into account
Number of floors	15–20 floors
Structure	Wall-column structure of reinforced concrete
Concrete strength	24 MPa for all floors

construction materials classified as national government LCI database and year 2003 industrial association Table [29–32]. Expression (1) shows the calculation of CO_2 generation in the material production stage:

$$\text{amount of } CO_2 \text{ generation in material production stage} = \sum(CO_2 \text{ emitting major construction materials used amount} \times CO_2 \text{ unit}) \quad (1)$$

3.2.3. *Material transport stage*

The amount of CO_2 generated in the material transport stage is calculated by measuring the amount of oil consumed by freight vehicles transporting major CO_2-emitting construction materials to the building site.

To that end, figures on the transportation distance to the site, on the type of freight transport vehicle, the standard fuel consumption rate and the number of vehicles used to transport each major CO_2-emitting construction material are required.

Therefore, in this study data on the load capacity of freight vehicles as specified in a table of standard construction resource costs and data on the types of transport vehicles principally used in the field were arranged according to each material the vehicles carried. Then, after calculating the number of freight vehicles used, the amount of oil consumed in the transport stage was calculated by determining the distance to the construction site and the standard fuel consumption rate of each vehicle [33]. A listing of vehicles used to transport each material and specifications by vehicle type are shown in Table 7. Expressions (2) and (3) indicate the amounts of oil consumed and CO_2 generated in each transportation stage:

$$\text{amount of oil use in transport stage} = \frac{\text{quantity calculated for each material}/\text{amount of freight vehicle load}) \times \text{disane (km)}}{\text{freight vehicle fuel consumption rate (km/l)}} \quad (2)$$

$$\text{amount of } CO_2 \text{ generated in material transport stage} = \sum(\text{amount of oil use in transport stage} \times CO_2 \text{ unit}) \quad (3)$$

3.2.4. *Building construction stage*

In the construction stage, the amount of CO_2 is calculated as the sum of the amounts of oil and electricity consumed by the construction machinery, the transportation equipment, the field office and other facilities used for the construction of the building. However, because construction conditions and methods of

Table 4
Contents of CO_2 emitting major construction materials quantity calculation.

w	Article	Standard	Unit	36 m²		
				2-Unit flat type	4-Unit flat type	4-Unit tower type
1	Ready mixed concrete	25-240-15	m³	518.83	1,037.66	1,068.79
		25-210-15	m³	1,426.66	2,853.32	2,938.92
	Sub-total		m³	1,945.49	3,890.98	4,007.71
2	Reinforced steel	H10	ton	159.74	319.48	329.07
		H13	ton	82.93	165.87	170.84
		H16	ton	30.64	61.28	63.12
		H19	ton	30.23	60.46	62.28
		H22	ton	93.15	186.30	191.88
		H25	ton	11.44	22.88	23.56
	Sub-total		ton	408.14	816.27	840.76
3	Plywood mould	3 times (lumber)	m²	6,089.25	12,178.50	12,543.85
	Plywood mould	Wall (Euro form)	m²	10,797.23	21,594.46	22,242.30
	Sub-total		m²	16,886.48	33,772.96	34,786.15
	Gang form	Elev./pit	m²	719.82	1,439.63	1,482.82
	Gang form	Ribbed side wall	m²	622.54	1,245.09	1,282.44
	Sub-total		m²	1,342.36	2,684.72	2,765.26
4	Concrete product		m³	20.67	41.33	41.33
	Cement brick	0.5B	m²	825.89	1,546.88	1,651.79
	Cement brick	1.0B	m²	–	–	–
	Cement		Bag	2,047.60	4,197.36	4,142.72
	Sand		m³	156.54	315.82	317.98
5	Industrial plastic product	T59	m²	692.87	1,291.77	1,385.73
	Laminated paper board	T79	m²	546.19	546.19	1,092.37
	Insulator preventing condensation	T9	m²	253.94	402.44	507.87
	Vinyl floor paper		m²	231.79	463.58	463.58
	PVC ceiling panel	Ceiling of the bathroom	m²	104.10	208.20	208.20
	PVC rain leader pipe	Φ150	m	218.00	348.00	348.00
6	Water-based paint	Inside wall, 3 times	m²	3,175.75	6,507.98	7,701.19
	Water-based paint	Inside ceiling, 3 times	m²	182.10	687.19	687.19
	Sub-total		m²	3,357.85	7,195.17	8,388.38
	Ceramin paint	3 times	m²	48.42	138.15	138.15
	Anti-corrosive paint		m²	247.00	643.00	643.00
	Pattern coat		m²	922.02	1,400.88	1,400.88
	Multi-color paint	3 times	m²	328.20	519.60	519.60

equipment use differ among the construction sites and it's difficult to obtain data for construction diaries, in this study calculations of the average amount of energy use by floor area in each construction stage were derived by analyzing existing research data [34]:

$$DPA = 2.39 \times TFA \tag{4}$$

$$GPA = 0.05 \times TFA \tag{5}$$

$$EPA = 10.47 \times TFA \tag{6}$$

Here, DPA indicates the amount of light oil use [l]; GPA indicates the amount of gasoline used [l]; EPA indicates the amount of electricity used [kW h]; and TFA building floor area [m²], and the

Table 5
Unit work cost of plywood among CO_2 emitting major construction material.

No.	Article	Standard	Unit	Quantity	36 m²		
					2-Unit flat type	4-Unit flat type	4-Unit tower type
3	Plywood mould	3 times (Lumber)	m²		6,089.25	12,178.50	12,543.85
	Waterproof plywood	1st grade, 12 mm × mm1220 × 2440 mm (m²)	m²	0.3656	2,226.23	4,452.46	4,586.03
	Rectangular lumber	Radiata pine (m³)	m³	0.0134	81.60	163.19	168.09
	Wire	Annealing, 4.0 mm	kg	0.1336	813.52	1,627.05	1,675.86
	Nail	Common type, N 75	kg	0.0922	561.43	1,122.86	1,156.54
	Stripper	For wood (water-based)	l	0.0875	532.81	1,065.62	1,097.59
	Plywood mould	Wall (Euro form)	m²		10,797.23	21,594.46	22,242.30
	Metal form (Euro form)	600 mm × 1200 mm × 63.5 mm	Sheet	0.0710	766.60	1,533.21	1,579.20
	Metal form (Euro form)	Inside wall corner panel, (200 + 200)1200	Sheet	0.0020	21.59	43.19	44.48
	Steel accessory of mould	Wedge pin, 90 mm	Q'TY	1.9002	20,516.90	41,033.80	42,264.81
	Steel accessory of mould	Flat tie, *L* = 200 mm	Q'TY	2.0026	21,622.53	43,245.07	44,542.42
	Steel pipe scaffolding	Scaffolding pipe, 48.6 mm × 2.3 mm	M	0.0773	834.63	1,669.25	1,719.33
	Steel accessory of mould	Whale hook, steel level (large)	Q'TY	0.2827	3,052.38	6,104.75	6,287.90
	Stripper	For wood (water-based)	l	0.0125	134.97	269.93	278.03
	Gang form	Elev./pit	m²		719.82	1,439.63	1,482.82
	Gang form	Ribbed side wall	m²		622.54	1,245.09	1,282.44
	Sub-total				1,342.36	2,684.72	2,765.26

Table 6
CO_2 emitting major construction material unit database.

No	Article	Korea Institute of Construction Technology		Korea Environmental Industry Technology Institute		Inter-Industry Analysis (Domestic)		Inter-Industry Analysis (Domestic & Overseas)	
		Amount of CO_2 Emission	Unit	Amount of CO_2 Emission	Unit	Amount of CO_2 Emission	Unit	Amount of CO_2 Emission	Unit
1	Steel equal angles	0.395	CO_2-kg/kg			2.026	CO_2-kg/kg	5.186	CO_2-kg/kg
2	Steel channels	0.395	CO_2-kg/kg						
3	Steel I beams	0.394	CO_2-kg/kg						
4	Steel H beams	0.388	CO_2-kg/kg						
5	General deformed iron bar	0.386	CO_2-kg/kg			1.646	CO_2-kg/kg	4.417	CO_2-kg/kg
6	High-tension deformed iron bar	0.396	CO_2-kg/kg						
7	Sand (General)	3.576	CO_2-kg/m^3			5.332	CO_2-kg/m^3	8.920	CO_2-kg/m^3
8	River sand	1.590	CO_2-kg/m^3						
9	Sea sand	2.097	CO_2-kg/m^3						
10	Ground sand	0.254	CO_2-kg/m^3						
11	Forest sand	5.016	CO_2-kg/m^3						
12	Gravel	11.146	CO_2-kg/m^3			5.157	CO_2-kg/m^3	8.627	CO_2-kg/m^3
13	REMICON transport (8-ton dump truck)	1.091	CO_2-kg/m^3*km						
14	REMICON transport (10.5-ton dump truck)	1.234	CO_2-kg/m^3*km						
15	REMICON transport (15-ton dump truck)	1.005	CO_2-kg/m^3*km						
16	REMICON transport (Concrete mixer truck)	0.660	CO_2-kg/m^3*km						
17	Shaped steel works	29,842.766	CO_2-kg/10m^3						
18	REMICON works	186.678	CO_2-kg/m^2						
19	PVC wall paper	1.188	CO_2-kg/m^2			24.367	CO_2-kg/kg	42.323	CO_2-kg/kg
20	Concrete brick	0.122	CO_2-kg/kg			0.189	CO_2-kg/each	0.353	CO_2-kg/each
70	Paint, Unsaturated polyester type			2,719.600	CO_2-kg/ton				
71	Paint, Water-soluble emulsion type			308.930	CO_2-kg/ton				
72	Paint, Water-soluble water type			1,066.900	CO_2-kg/ton				
73	Paint, Amino-alkyd type			783.340	CO_2-kg/ton				
74	Paint, Acrylic type			873.730	CO_2-kg/ton	11.445	CO_2-kg/kg	47.987	CO_2-kg/kg
75	Paint, Alkydenamel type			221.350	CO_2-kg/ton				
76	Paint, Epoxy type			3,157.900	CO_2-kg/ton	11.770	CO_2-kg/kg	49.348	CO_2-kg/kg
77	Paint, Urethane type			366,220.000	CO_2-kg/ton	9.393	CO_2-kg/kg	39.383	CO_2-kg/kg
78	REMICON, 25-210-12			400.132	CO_2-kg/m^3	171.504	CO_2-kg/m^3	321.088	CO_2-kg/m^3
79	REMICON, 25-210-15			409.981	CO_2-kg/m^3				
80	REMICON, 25-240-12			406.087	CO_2-kg/m^3				
81	REMICON, 25-240-15			419.572	CO_2-kg/m^3				
82	Gypsum board			135.015	CO_2-kg/kg				
83	Cement			1,048.800	CO_2-kg/ton	0.497	CO_2-kg/kg	0.980	CO_2-kg/kg
84	Glass wool			157.033	CO_2-kg/kg				
85	Sheet glass			750.830	CO_2-kg/ton				
86	Glass wool board			128.473	CO_2-kg/kg				
87	Glass wool pipe cover			147.178	CO_2-kg/kg				

Table 7
Selection of transport vehicle by each material.

Material	Transport vehicle	Load capacity	Standard fuel consumption rate (km/l)
Ready mixed concrete	Ready mixed concrete truck	6 m^3	2.44
Reinforced steel	20 ton trailer	20 ton	3.1
Rectangular lumber	8 ton truck	8 ton	4.5
Plywood mold	8 ton truck	8 ton	4.5
Euro form	8 ton truck	8 ton	4.5
Release agent	1 ton truck	1 ton	11.2
Paints	1 ton truck	1 ton	11.2
Cement brick wall	8 ton truck	3900 sheets	4.5
Cement	8 ton truck	8 ton	4.5
Sand	8 ton truck	8 ton	4.5

amount of CO_2 generated in building construction stage can be calculated:

$$\text{amount of } CO_2 \text{ generated in the building construction stage} = \sum(\text{amount of each energy in building construction stage} \times CO_2 \text{ unit}) \quad (7)$$

3.3. Operation stage

3.3.1. Overview

In the operation stage, calculations of the amount of CO_2 generated are derived by analyzing the total amount of energy consumed from electricity, oil and city gas during the period when the building is in use. Methods of assessing the amount of CO_2 generated include the following: using the results of a computer simulation analysis of the measured amount of energy use, using the computer model to estimate and analyze the amounts of energy used in the existing building, and using data on energy consumption and CO_2 emissions provided by the national government and public organizations.

In this study, the amounts of energy used in the building operation stage were calculated according to construction standards and detailed performance-related instructions pertaining to an environmentally friendly house specified by the Green Home Certification System developed by the Korean Ministry of Land, Transportation and Maritime Affairs.

3.3.2. Assessment method

The assessment of the Korea Green Home Certification System depends on location and dedicated area. The system can calculate the amount of energy consumption for heating load, rapid heating load, electric power load, and heat source load based on each type of household unit. Table 8 shows the calculation of energy by the items of the Green Home Certification System.

The system assesses environmentally friendly technical elements incorporated into the construction of the housing units. These elements are designed to reduce energy use and CO_2 emissions in housing units, and are divided into items that can be assessed quantitatively and those that cannot. Assessment of environmentally friendly housing is performed with an emphasis on elements that can be assessed quantitatively. Quantitative items are applied to an environmentally friendly house by being specified as recommended or mandatory.

The amount of energy consumption calculated through this system is used to determine CO_2 emissions through the use of CO_2 unit by energy sources proposed by the Green Home Certification System. The calculation is shown in Expression (8):

$$\text{amount of } CO_2 \text{ generated in building operation stage} = \sum(\text{amount of energy consumption in operation stage} \times CO_2 \text{ unit}) \times \text{life span} \quad (8)$$

3.4. Maintenance stage

3.4.1. Overview

In the maintenance stage, CO_2 emissions can be assessed by measuring the amount of repairs and replacements of apartment elements arising from deterioration, damage or loss of construction materials occurring during the life cycle of the building. In this study, CO_2 levels associated with the maintenance stage were calculated by determining the repair cycle and repair rate pertaining to construction materials used in the maintenance work performed on an apartment building based on a long-term repair plan established in 1982 by the Korean Ministry of Land and

Table 8
Method of calculating energy by each item in green home certification system.

Class	Calculation expression
Heating load	
Standard	Standard house yearly heating load calculation expression × number of applicable household
Assessment	Heating load × standard house yearly heating load by each part of building calculated through overall heat transfer coefficient
Rapid heating load	
Standard	Standard house yearly rapid heating load calculation expression × number of applicable households
Assessment	(Standard house yearly rapid heating load – amount of rapid heating load reduction by the use of solar cell use) × number of applicable households
Electric load	
Standard	Standard house yearly power load calculation expression × number of applicable households
Assessment	(Standard yearly power load – amount of electric power load reduction by the households by solar heat, wind power and geothermal power technology) × number of applicable households
Heat source load	
Standard	Energy consumption rate of individual boilers of 84% efficiency
Assessment	Heat source system energy consumption rate

Table 9
Repair cycle and repair rate of outside finishing material by construction parts.

Class	Construction type	Repair method	Repair cycle (year)	Repair rate (%)
Roof	Mortar finishing	Partial repair	5	18
		Overall repair	15	100
External wall	Mortar finishing	Partial repair	8	15
		Overall repair	25	100
	Water paint	Overall repair	5	100
Ceiling	Mortar finishing	Overall repair	30	100
	Water paint	Overall repair	5	100
	Oil paint	Overall repair	5	100
Internal wall	Water paint	Overall repair	5	100
	Oil paint	Overall repair	5	100
Floor	Mortar finishing	Partial repair	5	15
		Overall repair	20	100

Maritime Affairs. Table 9 shows the repair cycle and repair rate of outside finishing materials.

3.4.2. Assessment method

The amount of material used in a building's maintenance stage, can be determined by the repair cycle and the repair rate. In this study, the usage rates of mortar and paint were surveyed to determine the amounts of CO_2 emissions linked to these construction materials. The amount of construction material used in the maintenance stage of the building's life cycle was then calculated according to Expression (9). Using the unit database proposed in this study, the amount of CO_2 generated during the maintenance stage was then calculated. The calculation is shown in Expression (10):

$$\text{amount of materials used in the maintenance stage} = \sum(\text{amount of materials used in construction stage} \times \text{material investment rate}) \quad (9)$$

$$\text{amount of } CO_2 \text{ generated in the maintenance and management stage} = \sum(\text{amount of materials used in maintenance stage} \times CO_2 \text{ unit}) \quad (10)$$

3.5. Dissolution/disposal stage

3.5.1. Overview

Dissolution/disposal stage refers to the stage in which the amount of CO_2 generated in the process of dismantling and disposing of a building is assessed. The disposal process is classified into a waste transport stage, a waste treatment stage, and a burial stage.

In this study, the CO_2 generated in the disposal stage came from the disposal of major structural materials, which is to say concrete, reinforced steel, plain concrete and concrete blocks. In calculating the amount of disposed wastes, rates at which the wastes were recycled were considered. Fig. 3 shows the process of evaluating CO_2 emissions in the dissolution/disposal stage.

3.5.2. Dissolution stage

In the dissolution stage of construction, dissolutions are executed mainly by large machines and through explosions. The machinery, of course, uses oil. Therefore in this study, the amount of CO_2 generated from the consumption of oil by the dissolution equipment was calculated. For this calculation the study surveyed the mechanical construction methods and equipment generally used for the demolition of apartment buildings in Korea. The study analyzed the amount of oil consumed by the various types of dissolution equipment. This amount can vary depending on the

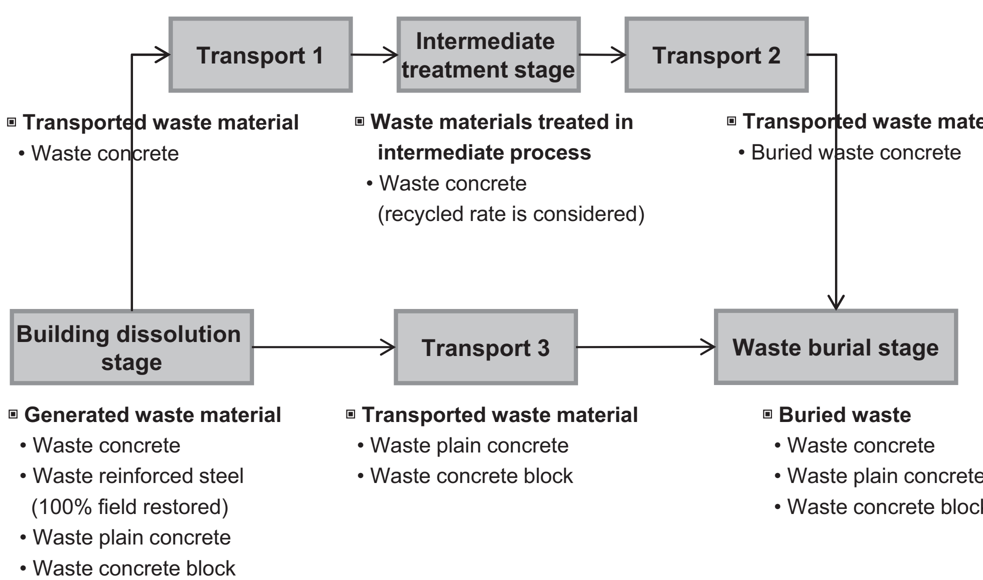

Fig. 3. Process of assessing CO_2 in dissolution/disposal stage.

Table 10
Amount of oil consumption by the combination of dissolution equipment.

Equipment combination	Basic assumption	Work amount (m^3/h)	Fuel consumption amount (l/h)	Fuel consumption amount (l/m^3)	Fuel consumption amount (l/ton)
Backhoe (1.0 m^3) + giant breaker (0.7 m^3)	Reinforced concrete thickness 30 cm	2.45	11.60	4.7347	3.6421
Pavement breaker (2 at 25 kg) + air compressor (3.5 m^3/min)	Reinforced concrete	3.20	9.92	3.1000	2.3846
Backhoe (1.0 m^3) + crusher (1.0 m^3) + giant breaker (0.7 m^3)	Reinforced concrete	3.50	19.50	5.5714	4.2857
Backhoe (0.4 m^3) + breaker (0.4 m^3)	Reinforced concrete	1.60	9.90	6.1875	4.7596
Backhoe (1.0 m^3) + crusher (2 at 137 ton)	Reinforced concrete	11.80	19.50	1.6525	1.2712
Motorized cutter (25HP)	Reinforced concrete thickness 15 cm	2.5 (m/h)	5.60	2.2400	1.7231
Crane (unlimited trajectory 50 ton) + steel ball (1.5 ton)	Reinforced concrete	5.63	12.00	2.1333	1.6410
Payload (3.5 m^3)	Sand stack	37.34	19.90	0.5329	0.4100
Dump (15 ton)	Transport distance 10 km	7.61	22.10	2.9041	2.2339

size of the equipment, its age, and the skill level of the operators of the machinery. Using this data, the study built up a database that reflected standard construction resource costs and unit work costs.

In addition, unlike previous studies in Korea that calculated the amount of construction waste according to floor area based on standard construction resource costs, this study determined the amount of major CO_2-emitting construction materials and calculated the amount of waste material by applying the volume increase rate (1.5 volume rate after dissolution over the rate measured before dissolution) of waste material by construction standard resource cost. Expressions (11), (12) and (13) show the calculation of the amount of waste generated in each dissolution stage, the amount of oil consumed by the dissolution equipment, and the amount of CO_2 generated. Table 10 shows the work amount and oil consumption amount measure by the number of hours the dissolution equipment was in operation [35]:

$$\text{amount of waste generated in dissolution stage} = \sum(\text{amount of materials used in construction stage} \times \text{volume increase rate}) \quad (11)$$

$$\text{amount of oil consumed by dissolution equipment} = \sum(\text{amount of generated waste} \times \text{amount of fuel consumed by dissolution equipment}) \quad (12)$$

$$\text{Amount of } CO_2 \text{ generated in dissolution stage} = \sum(\text{amount of fuel consumed by dissolution equipment} \times CO_2 \text{ unit}) \quad (13)$$

3.5.3. Disposal stage

The disposal stage was divided into the waste transport process, the intermediate treatment process and the burial process, and the method of calculating CO_2 in each stage was proposed.

(1) Waste transport process

The amount of energy consumed during the waste transport process can be calculated according to the amount of oil consumed by the vehicle transporting the waste generated in the dissolution stage to a burial location or an intermediate treatment site; as the amount of waste material calculated in the dissolution stage; and measuring the distance to the burial location or intermediate treatment location, taking into account the types of vehicles used to transport the waste and their standard rate of fuel consumption. Expressions (13) and (14) show the calculations of the amount of oil consumed during the waste transport stage and the amount of CO_2 generated:

$$\text{amount of oil used in waste transport stage} = \frac{(\text{amount of each waste material}/\text{amount of freight vehicle load}) \times \text{distance (km)}}{\text{freight vehicle fuel consumption rate (km/l)}} \quad (13)$$

$$\text{amount of } CO_2 \text{ generated during waste transport stage} = \sum(\text{amount of oil used during waste transport stage} \times CO_2 \text{ unit}) \quad (14)$$

(2) Intermediate waste treatment process

In the intermediate treatment process, which refers to the work of crushing and sorting waste materials generated in the field, waste concrete generally makes up the greatest portion of the total. In this stage, which is conducted in connection with the burial process, the amount of CO_2 generated was calculated using existing research data on the amount of energy used during intermediate treatment. This data was developed through a field survey that considered the rate at which waste concrete was recycled. Expression (15) shows the calculation of CO_2 generated in the intermediate treatment process. Table 11 shows the amount of energy consumed during the intermediate treatment process [36]:

$$\text{amount of } CO_2 \text{ generated in the intermediate treatment process stage} = \sum(\text{amount of energy consumed during intermediate treatment} \times CO_2 \text{ unit}) \quad (15)$$

(3) Waste burial process

This process is the stage in which waste that cannot be recycled from the dissolution stage is buried. In this stage, plain concrete and concrete blocks generated in the field and waste concrete classified in the intermediate treatment process are buried. Therefore, in this study, the amount of waste buried is calculated according to the method proposed in the "Section 3.5.2." The amount of CO_2 generated in the waste burial process is calculated by measuring the amount of oil used by bulldozers and compacters operating at the burial site. Expression (16) shows the calculation of CO_2 generated in the burial stage.

Table 11
Amount of energy consumed in intermediate treatment process stage.

Class	Light oil (l/ton)	Electric power (kW h/ton)
Energy consumption amount	0.682	1.70

Table 12
Amount of oil consumed by burial equipment.

Class	Burial equipment and specification	Light oil (l/ton)
Energy consumption amount + compactor (32 ton)	Dozer (D8N, 15PL, 6PL)	0.15

Table 13
Architectural overview of existing apartment house and standard apartment house.

Item	Overview of construction	
	Existing apartment house	General standard apartment house
Lettable area	85.65 m^2	84 m^2
Number of floors	20	20
Height of a floor	2.9 m	2.9 m
Number of households	40	40
Combination of living units	2-unit combined flat type	2-unit combined flat type
Structure	Reinforced concrete	Reinforced concrete

Table 12 shows the amount of oil consumed by the burial equipment:

$$\text{amount of } CO_2 \text{ generated in burial stage} = \sum(\text{amount of oil consumed by burial equipment} \times CO_2 \text{ unit}) \tag{16}$$

4. Study on the case of life cycle CO_2 assessment

4.1. Overview

To assess the potential of the apartment house life cycle CO_2 simple assessment system proposed in this study, we compared and analyzed assessments derived from that system with the results of existing assessments of life cycle CO_2 done on existing apartment buildings that were completed in 2004.

4.2. Assessment conditions

Existing apartment houses are composed of a plain area 85 m^2, they are 20 stories high and contain a total of 40 housing units. Standard apartment houses were classified to conform to assessment conditions very similar to those of existing apartment houses by assuming a plain area of 84 m^2, heights of 20 stories and housing units totaling 40 households. Table 13 shows the architectural overview of existing apartment houses and standard apartment houses, and below are shown the assumptions for the assessment of existing apartment house and standard apartment house life cycle CO_2:

Assumptions

- transport distance of each material in the construction material transport stage: 30 km;
- building anticipated lifespan: 60 years;
- rate of waste concrete recycling: 70%;
- distance from the field to waste treatment plant: 30 km;
- distance from the field to intermediate treatment plant: 20 km;
- distance from intermediate treatment plant to waste treatment plant: 20 km.

4.3. Assessment method

4.3.1. Method of existing apartment building CO_2 assessment

The amount of CO_2 generated in the construction stage was assessed according to a direct input method developed by industrial association analysis based on the quantity of materials used in the building's construction, calculated after the completion of construction. The amount of CO_2 in the operation stage was

Table 14
Comparison of CO_2 assessment methods.

Stage	Existing apartment houses	Standard apartment houses
Construction stage	Quantity calculation, direct input industrial association analysis method	Major materials, automatic quantity calculation mixed analysis method
Operation stage	Measured amount of yearly used energy	Green Home Certification System
Maintenance stage	Estimation model expression (amount of CO_2 emitted per floor area)	Repair rate, repair cycle using method
Dissolution/disposal stage	Estimation model expression (amount of CO_2 emitted per floor area)	Dissolution equipment and recycled rate, disposal method

Table 15
Results of assessment of CO_2 of existing apartment houses and standard apartment houses.

CO_2 items	Existing apartment houses		Standard apartment houses	
	Emission amount (ton-CO_2)	Ratio (%)	Emission amount (ton-CO_2)	Ratio (%)
Construction stage				
Material production	2,005.75	17.23	1,554.00	11.08
Material transport	41.86	0.35	43.45	0.31
Material installation	108.72	0.93	44.16	0.31
Sub-total	2,156.33	18.52	1,641.61	11.71
Operation stage	9,253.15	79.49	12,012.45	85.71
Maintenance stage	200.25	1.72	165.48	1.18
Dissolution/disposal stage				
Dissolution	0.41	0.003	130.06	0.92
Transport	29.94	0.25	55.88	0.39
Disposal	–	–	8.18	0.06
Sub-total	30.35	0.26	194.12	1.39
Total	11,640.08	100	14,013.66	100

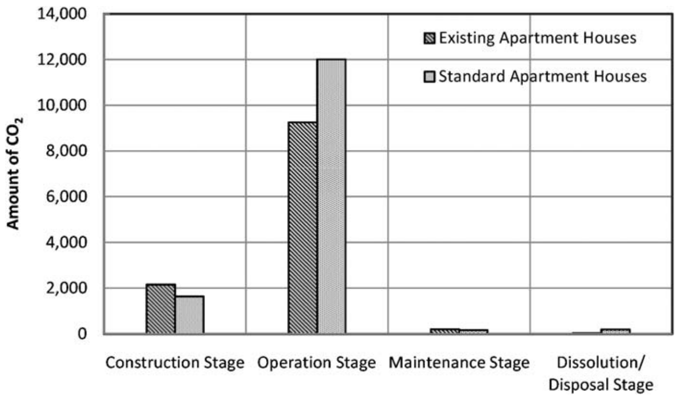

Fig. 4. Results of assessment of CO_2 amount of each stage.

calculated by assuming the amount of actual energy consumption for one year. In the cases of the maintenance stage and the dissolution/disposal stage, the amount of CO_2 generated was estimated according to a computer model based on the floor area of the building.

4.3.2. Method of assessing CO_2 of a standard apartment house

In the construction stage, CO_2 emissions from major construction materials were calculated by the automatic quantity calculating method proposed in this study. The amount of CO_2 was calculated based on the major CO_2-emitting construction materials unit database proposed in this study. In the operation stage, the amount of energy used in the building's operations was calculated according to the construction standard for environmentally friendly dwellings specified by the aforementioned Green Home Certification System and its detailed instructions pertaining to performance. In the maintenance stage, the quantity of repair materials was calculated by the automatic calculating method, and the amount of CO_2 was assessed by taking into consideration repair rates and repair intervals. In the dissolution/disposal stage, the amount of CO_2 emissions was assessed by calculating the dissolution amount of construction materials determined by the automatic quantity calculation method. Table 14 shows the method of assessing CO_2 by the stages for existing apartment houses and standard apartment houses.

4.4. Assessment results

Table 15 and Figs. 4 and 5 show the results of the assessment of the life cycle CO_2 emissions of existing apartment houses and standard apartment houses. According to Table 15, the amounts of

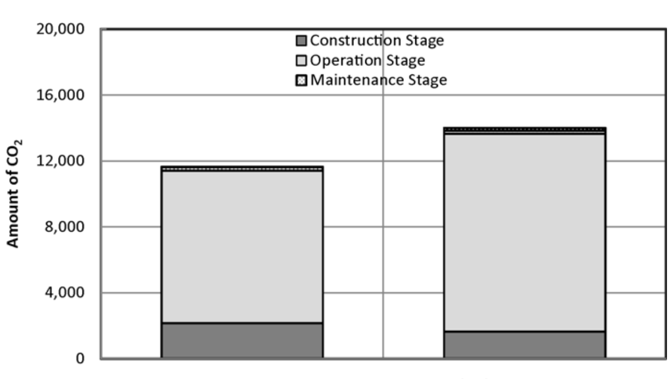

Fig. 5. Results of assessment of CO_2 amount of existing apartment houses and standard apartment houses.

CO_2 emissions calculated by the material production in the construction stage were assessed 2005.75 ton-CO_2 for existing apartment houses and 1554.00 ton-CO_2 for 1554.00 ton-CO_2 for standard apartment houses which is equivalent to 77% over existing apartment houses. This is a result very close to the 80% CO_2 emission amount generated by the production of construction material discussed earlier in this study. In the case of the transportation of materials, the value 43.45 ton-CO_2 is assessed to be about 103% of 41.86 ton-CO_2, the amount of CO_2 previously calculated. The amounts of CO_2 calculated for the construction stage were assessed 2156.33 ton-CO_2 for existing apartment houses and 1641.61 ton-CO_2 for standard apartment houses. Furthermore, in the operation stage, the amount of CO_2 for standard apartment houses, 12,012.45 ton-CO_2, was assessed somewhat higher at about 130% over 9253.15 ton-CO_2 the amount of CO_2 emission of existing apartment houses. However, in the maintenance stage, existing apartment houses and standard apartment houses showed similar assessment results.

On the other hand, in the case of the dissolution/disposal stage, the amount of CO_2 generated was assessed higher in standard apartment houses than in existing apartment houses. That is presumably due to the fact that the disposal process is not an applicable factor when considering existing apartment houses. Furthermore, the applied estimation model is intended for use with respect to general buildings rather than apartment houses, which are the focus of this study. Consequently, it differs from the amount of CO_2 generated in the dissolution/disposal stage of actual materials as it applies to standard apartment houses.

5. Conclusions

This study was conducted to develop a simple life cycle CO_2 assessment that can be used during the construction planning and basic design stage to calculate the life cycle CO_2 emissions of apartment houses. The study reached the following conclusions:

1. The life cycle of apartment houses was classified into a construction stage, an operation stage, a maintenance stage and a dissolution/disposal stage, and a method of assessing CO_2 emissions in each stage was proposed.
2. A total of 90 types of standard apartment houses that include dedicated area, number of housing units, and number of stories were proposed based on the five planes proposed in the Green Home Certification System of Korea.
3. A method was devised to automatically calculate CO_2 emissions from major construction materials that account for more than 80% of CO_2 emissions in building construction.
4. The calculation of CO_2 emissions by material production during the construction stage reached effective results very close to the 80% CO_2 emission amount derived from by materials used in building construction discussed earlier in this study.
5. The CO_2 amount for the life cycle of the standard apartment houses proposed in this study, 14,013.66 ton-CO_2, was assessed to be similar to the 11,640.08 ton-CO_2 of existing apartment houses. Therefore, it is judged that the life cycle CO_2 emissions of apartment houses can be effectively assessed in the construction planning and basic design stage through the use of the simple life cycle CO_2 assessment system for apartment houses proposed in this study.

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